IMM based Augmented EKF for RF Seeker Filter

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***Abstract*- Radio frequency seeker filter design for homing guidance requirements are highly demanding and challenging. Seeker data is highly noisy and is characterized by correlation, non-guassian due to target glint and modulated by radar cross section fluctuations. Over and above there will be periodic data loss due to eclipsing. For generating smooth homing guidance commands an efficient filter having minimum lag and maximum seeker noise attenuation capability is required. This paper presents an interacting multiple model seeker filter with extended Kalman filter as mode-matched filter which operates in closed homing guidance loop to generate required guidance commands to intercept maneuvering air-breathing targets. The performance of the seeker filter is evaluated using simulation of different interceptor-target engagement scenarios with different target maneuver profiles.**

I. INTRODUCTION

RF Seeker is an active radar on-board an intercepting (homing guidance) missile. Seeker filter is a target state estimator which is an important subsystem in modern homing guidance system of advanced missile. Seeker filter is required for two reasons [1]. Firstly, the measurements provided by on-board active RF seeker of an intercepting missile are often corrupted by noise, and are not in a form usable by the guidance law. Secondly, advanced guidance laws require additional information about the target such as its acceleration components, which cannot be provided by the on-board sensors.

RF Seeker filter design for homing guidance requirements are highly challenging. Very low filter lag (to meet very low guidance time constant for air breathing targets with evasive maneuvers at short range to go), on-line seeker filter lag control (for closed loop guidance stability and miss distance) and high attenuation of seeker noise which is correlated, non-Gaussian and modulated by radar cross section (RCS) fluctuation are some of the challenges that need to be addressed. Air breathing targets against which homing guidance is required are assumed to be maneuvering in an open-loop fashion, without any explicit goal or strategy. This assumption leads to purely reactive target state estimators, often producing sluggish state estimator response in the presence of agile targets. An ideal approach to preserving the agility of the target state estimator without sacrificing its accuracy is to model the target motion with a set of models that characterize the target motion all the time and a switching logic. The switching logic is then allowed to select any one of these models at any instant of time. Thus, to an estimator, at each time instant, the target model appears to follow like one of these models. The resulting target state estimator consists of a bank of Kalman filters whose outputs are blended using a hypothesis-testing algorithm. This approach is called Interacting Multiple Model (IMM) estimation technique [2]. The physical model of the target is assumed to be known, but the exact maneuver strategy is parameterized and then determined online together with the target states. Since the target maneuvering logic is adaptively determined, the resulting estimation scheme can be expected to have agile response to any changes in the target behavior and there by filter time lag is expected to be well under control.

This paper presents an interacting multiple model based augmented extended Kalman filter (IMM-AEKF) with constant acceleration (CA) and constant jerk (CJ) models [3] as RF seeker filter for tracking air breathing target performing evasive maneuver. The major challenge in processing the seeker data, especially in end game, is glint noise [4] which is a non-Gaussian noise with heavy tail distribution. The glint noise is a function of target aspect, RCS fluctuation and range to go. Obviously, when the range to go is less, the effect of glint noise (if not accounted properly) on guidance will be more and this would in turn result in large miss distances. The glint noise and RCS fluctuations present in seeker data are handled as augmented states in the filter algorithm and hence the name augmented EKF. Section II of the paper includes the system architecture used to simulate missile-target engagement using realistic RF seeker data and processing it through seeker filter to provide the necessary guidance command to achieve minimum miss distance within specified time to go. The data simulation results and discussion are provided in section III. Concluding remarks are provided in section IV.

II. MISSILE-TARGET ENGAGEMENT SIMULATION

MATLAB / SIMULINK based aerospace block set is used to simulate close loop missile-target engagement in 6 degree of freedom (3 degree of freedom separately for pitch plane and yaw plane) and the seeker filter performance is validated using several realistic interceptor-target engagement scenarios. Figure 1 shows the MATLAB/SIMULINK block diagram of interceptor-target engagement simulation with seeker filter. In present simulation, it is assumed that missile has no roll motion. The basic components of the SIMULINK block are presented below:

A. Missile-Target Separation

The target trajectory is simulated (as point mass model) using following state equations:

$$\dot{V}_t = 0.0 \tag{1}$$

$$\dot{\gamma}_t = \eta_{vt} \frac{g}{V_t} \tag{2}$$

$$\dot{\phi}_t = \frac{\eta_{ht} g}{V_t \cos\gamma_t} \tag{3}$$

$$\dot{h}_t = V_t \sin\gamma_t \tag{4}$$

$$\dot{y}_t = V_t \cos\gamma_t \sin\phi_t \tag{5}$$

$$\dot{x}_t = V_t \cos\gamma_t \cos\phi_t \tag{6}$$

where, V_t is (a constant) speed of target, η_{vt} and η_{ht} are the load factors in pitch and yaw planes respectively, g (=9.8 m/s2) is the gravitational constant, ϕ_t and γ_t are azimuth and elevation of target and x_t, y_t, h_t are the target positions along inertial x, y, and z axis respectively.

Missile-Target Separation block (figure 1) receives relative positions of missile w.r.t. target in Cartesian (inertial) frame and converts it to relative range (or range to go) and elevation (pitch plane)/azimuth (yaw plane) angle. In pitch plane, relative range and elevation angle are computed using following formula:

$$\Delta x = x_t - x_m \tag{7}$$

$$\Delta h = h_t - h_m \tag{8}$$

$$\text{Range to go}: \quad r_{go} = \sqrt{\Delta x^2 + \Delta h^2} \tag{9}$$

$$\text{Elevation}: \quad \theta = a\tan\left(\frac{\Delta h}{\Delta x}\right) \tag{10}$$

where, x_t and h_t are the target positions along inertial x and z axis respectively and x_m and h_m are the missile positions in the same axis generated from missile '*Airframe and Auto-pilot*' SIMULINK block.

B. Seeker

The related angles in the seeker are presented in Figure 2 and are defined as: θ_{MA} = Missile body attitude w.r.t inertial reference axis, λ = Sight Line angle, (angle between inertial reference and missile-target axis) , θ_{LA} = Look up angle ($\theta_{LA} = \lambda - \theta_{MA}$), angle between missile body axis and missile-target axis, ϕ = Gimbal angle (angle between missile body axis and seeker dish axis), R = Radome slope error, de = dish error ($de = (\theta_{LA} - \phi) + R\phi$) (angle between seeker dish and apparent target axis).

Inputs to Seeker block are r_{go} (range to go), θ_{LA}, missile body angular rate- q (pitch plane)/ r (yaw plane), and demanded look angle $\theta^d{}_{LA}$ supplied by '*Guidance*' block during target search mode. The major components of seeker block include: i) *Tracker and Sightline Rate Estimator* which generates true LOS rate, and gimbal angle in LOS frame by using look angle θ_{LA}, missile body rate q (pitch plane) / r (yaw plane), and demanded look angle $\theta^d{}_{LA}$, ii) *Target Acquisition* which checks whether target is within field-of-view (FOV) of seeker or not, and *iii) Range and Closing Velocity Estimator which* computes range-to-go and closing velocity of missile w.r.t. target.

C. Seeker Filter – IMM-AEKF

This block is developed using MATLAB S-function. The inputs to the block are measured range, range rate, LOS angle, LOS rate, missile acceleration components. The outputs are estimated LOS rate and closing velocity used to generate guidance command. A 2-model interacting multiple model (IMM) Kalman filter, with constant acceleration (CA) and constant jerk (CJ), is considered for tracking the target executing evasive maneuver. The description of IMM filter is given in reference [5]. The initial mode probability is chosen as 0.9 for CA mode and 0.1 for CJ mode respectively. The mode transition matrix is computed based on target maneuver sojourn time. The filter model is formulated in Cartesian plane and processes the seeker measurements in LOS frame. Following are the state model and measurement model of the seeker filter in pitch plane:

State model:

CA model:

$$\Delta\dot{x} = \Delta V_x\,; \quad \Delta\dot{V}_x = a_{tx} - a_{mx}\,; \quad \dot{a}_{tx} = -\left(\frac{a_{tx}}{\tau_x}\right); \quad \dot{j}_{tx} = 0 \tag{11a}$$

$$\Delta\dot{z} = \Delta V_z\,; \quad \Delta\dot{V}_z = a_{tz} - a_{mz}\,; \quad \dot{a}_{tz} = -\left(\frac{a_{tz}}{\tau_z}\right); \quad \dot{j}_{jz} = 0$$

CJ model:

$$\Delta\dot{x} = \Delta V_x\,; \quad \Delta\dot{V}_x = a_{tx} - a_{mx}\,; \quad \dot{a}_{tx} = j_{tx}\,; \quad \dot{j}_{tx} = -\left(\frac{j_{tx}}{\tau_x}\right) \tag{11b}$$

$$\Delta\dot{z} = \Delta V_z\,; \quad \Delta\dot{V}_z = a_{tz} - a_{mz}\,; \quad \dot{a}_{tz} = j_{tz}\,; \quad \dot{j}_{jz} = -\left(\frac{j_{tz}}{\tau_z}\right)$$

where, $\Delta x, \Delta z$ are the relative positions of target w.r.t. missile, $\Delta V_x, \Delta V_z$ are the relative velocities, a_{tx}, a_{tz} are the target accelerations, j_{tx}, j_{tz} are the target jerks, a_{mx}, a_{mz} are the missile accelerations, and τ_x, τ_z are the correlation time constant.

Measurement model:

$$r_{go} = \sqrt{\Delta x^2+\Delta z^2} \quad ; \quad \dot{r}_{go} = \frac{\Delta x\Delta\dot{x}+\Delta z\Delta\dot{z}}{\sqrt{\Delta x^2+\Delta z^2}}$$

$$\lambda_e = tan^{-1}\left(\frac{\Delta z}{\Delta x}\right)+ gl\,int \;;\; \dot{\lambda}_e = \frac{\Delta x\Delta\dot{z}-\Delta z\Delta\dot{x}}{\Delta x^2+\Delta z^2} + K_v\, gl\,int \tag{12}$$

$$gl\,int = \frac{\alpha_{t\,arg\,et} LengthT\,arg\,et}{10 r_{go}}\left(\frac{\xi_1\xi_3+\xi_2\xi_4}{\xi_1^2+\xi_2^2+0.05}\right) \tag{13}$$

$$\xi_3 = \xi_{31} + a_{0g} \qquad \xi_4 = \xi_{41} + a_{0g} \tag{14}$$

where, $gl\,\mathrm{int}$ is the glint noise and K_v the track loop (ATL) gain (=0.2 for present case), $\alpha_{t\,arg\,et}$ and $LengthT\,arg\,et$ are target aspect and length of target respectively, and parameters such as $\xi_1, \xi_2, \xi_3, \xi_4, \xi_{31}, \xi_{41}, a_{0g}$ are related to states of glint noise and RCS fluctuation (details of computation of these parameters are not provided in this paper due to page limits).

D. Guidance

This block consists of Guidance processor and proportional navigation (PN) guidance law. Guidance processor is used to control the operational modes of the seeker such as i) target search, ii) target lock, iii) seeker guided, and iv) blind range. Target search mode is activated when “Acquire Flag” from ‘*Target Acquisition’* block is set to 1. In this mode guidance processor supplies demand look angle θ^d_{LA} to ‘*Seeker*’ block till the lost target is acquired again. After the target is acquired, guidance processor switches to target lock mode and remains there till the newly acquired time exceeds limit. After crossing the time limit, Guidance processor goes to seeker guided mode where the missile is guided using measurements of seeker. Blind zone is activated when range-to-go crosses certain minimum limit. Other than in the guided mode, a fixed value of demanded acceleration is supplied to PN guidance law. Guidance processor is also used to detonate the missile, if the seeker remains in target search mode for more than some maximum limit or range-to-go is too small.

E Missile Airframe and Auto-pilot

This block generates the required fin deflections to steer the missile towards the target using the demanded acceleration generated by PN guidance law. The components of this block are: i) *Atmospheric model*, ii) *Missile aerodynamics data base and* 3DOF missile *equations of motion* separately for *pitch plane* and *yaw plane* to generate missile body attitude θ_{MA} (pitch plane)/ ϕ_{MA} (yaw plane), body rates q / r and missile states such as x-y-z positions, velocities and accelerations in inertial frame, iii) *Auto-pilot model* which generates required fin demand, and iv) *Fin actuator model* to convert fin demand signal into appropriate fin deflections.

III. Data Simulation, Results and Discussion

Two sets of target trajectory data are simulated (using equations 1 to 6) with following specifications:

Data Set 1 of constant maneuver type with a) sampling interval = 10 milliseconds, b) total simulation time = 10.78 seconds, c) initial velocity $V_t(0)$ = 310 m/s, d) initial positions along inertial axis $x_t(0) = 8997$m, $y_t(0) = 0$m, $h_t(0) = 500$m e) initial azimuth angle ϕ_t =180deg, f) initial elevation angle γ_t =0deg, g) load factor in pitch plane η_{vt} = 6, and h) load factor in yaw plane η_{ht} = 6

Data Set 2 of evasive maneuver type with a) sampling interval = 10 milliseconds, b) total simulation time = 20 seconds, c) initial velocity $V_t(0)$ = 500 m/s, d) initial positions along inertial axis $x_t(0) = 9010$m, $y_t(0) = 0$, $h_t(0) = 500$m e) initial azimuth angle ϕ_t = 90 deg, f) initial elevation angle γ_t = 2 deg and g) load factors η_{vt} and η_{ht} are as given in Table I.

These target trajectory data are read into the missile (interceptor) simulation and the homing guidance performance of the missile under following cases are evaluated to bring out the advantage of using IMM-AEKF filter as seeker filter:

Case1: When seeker filter is not present in the guidance loop.

Case2: When well tuned low pass filter (with cutoff frequency of 10Hz) is used as seeker filter in the guidance loop.

Case3: When 2 model IMM-AEKF with CA and CJ models is used as seeker filter in the guidance loop.

With target trajectory data set I, missile guidance simulation is initiated with the following initial conditions: Initial positions along inertial axis $x_m(0) = 3$m , $y_m(0) = -0.1080$m , $h_m(0) = 500$m and Initial velocity $V_m(0)$ = 496 m/s. Table II shows the performance parameters of the homing guidance with and without seeker filter in the guidance loop. Similarly with target trajectory data set II, missile guidance simulation is initiated with following initial conditions: Initial positions along inertial axis $x_m(0) = 16$m , $y_m(0) = 0$m , $h_m(0) = 500$m and Initial velocity $V_m(0)$ = 1000 m/s. Table III shows the performance parameters of the homing guidance with and without seeker filter in the guidance loop.

In addition, figures 3 and 4 shows the missile-target engagement in pitch plane which shows early interception when the seeker filter is present in the guidance loop. Figure 5 and 6 shows the latax (lateral acceleration) demand on the missile generated by the guidance law with and without seeker filter in the guidance loop. These results indicate that with an efficient seeker filter the latex demand on the missile is reasonably low to achieve target interception. Figure 7 and 8 shows the noise attenuation achieved by low pass seeker filter and IMM based augmented EKF seeker filter. The noise attenuation factor (AF) is defined as

$$AF = \frac{X_t - \hat{X}}{X_t - X_m}$$

where X_t is the true value of the filtered state, X_m is measured value and $\hat{X}$ is the estimated value. It is expected from an optimal seeker filter that the noise attenuation factor is less than 0.1 over a window length of 10. Figures 7 and 8 show the noise attenuation achieved by IMM-AEKF seeker filter is slightly better.

Though a well tuned low pass filter and IMM based augmented EKF seeker filter produce reasonably low latax demand, the IMM-AEKF filter is a better choice because it not only achieves better noise attenuation but also generates additional information like target acceleration often required by advanced guidance laws (APN) through a kinematic model carried by the filter.

Table I: Load factors for data set 2

Time (seconds)	Load factor η_{vt} (pitch plane)	Load factor η_{ht} (yaw plane)
0.00 - 5	0	0
5.01 - 10	0	6
10.01 - 15	6	0
15.01 - 20	0	0

Table II: Guidance performance with target data I

Cases	Time to Intercept (sec)	Miss Distance (m)	Impact Ratio $\frac{V_m}{V_t}$	Closing Velocity (m/s)
No seeker filter in the guidance loop	11.01	9.97	6.14	600
Low pass filter in the guidance loop	10.64	9.75	6.84	680
IMM-AEKF in the guidance loop	10.67	9.50	6.72	660

Table III: Guidance performance with target data II

Cases	Time to Intercept (sec)	Miss Distance (m)	Impact Ratio $\frac{V_m}{V_t}$	Closing Velocity (m/s)
No seeker filter in the guidance loop	17.380	124.9	1.738	280
Low pass filter in the guidance loop	15.093	9.773	2.10	450
IMM-AEKF in the guidance loop	15.085	9.949	2.09	430

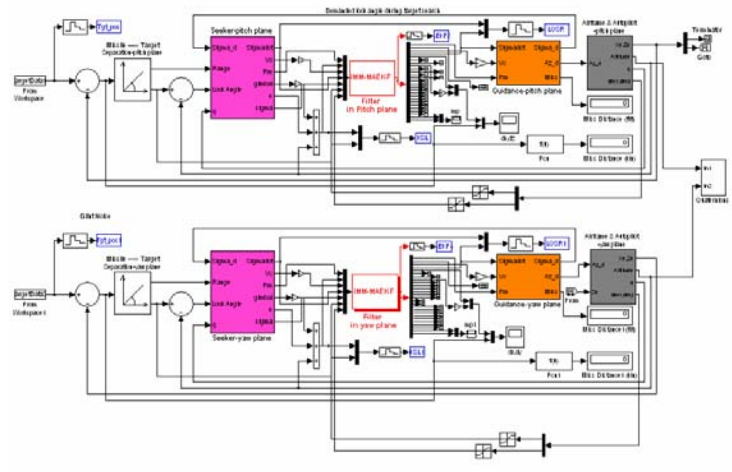

Figure. 1: MATLAB/SIMULINK block diagram of missile-target engagement simulation with seeker filter

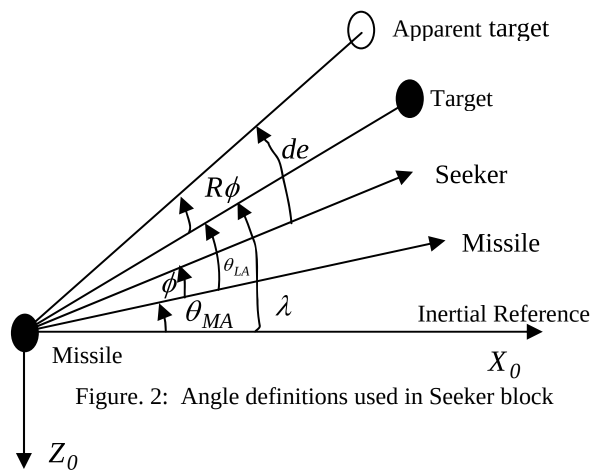

Figure. 2: Angle definitions used in Seeker block

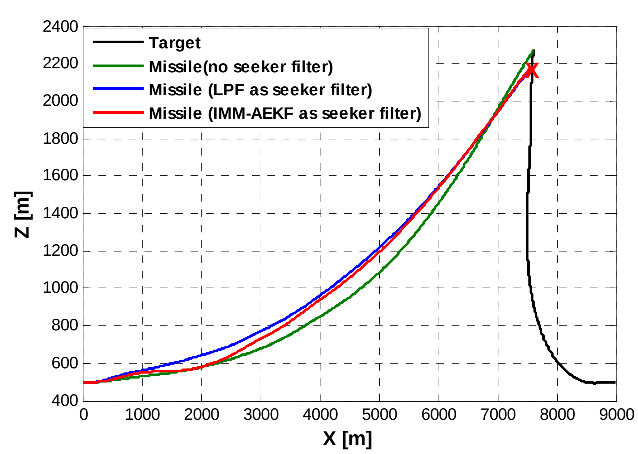

Figure 3: Missile–Target engagement trajectory (Data set I)

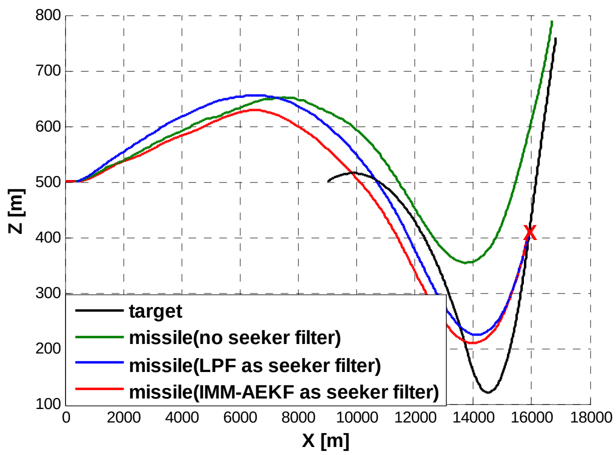

Figure 4: Missile–Target engagement trajectory (Data set II)

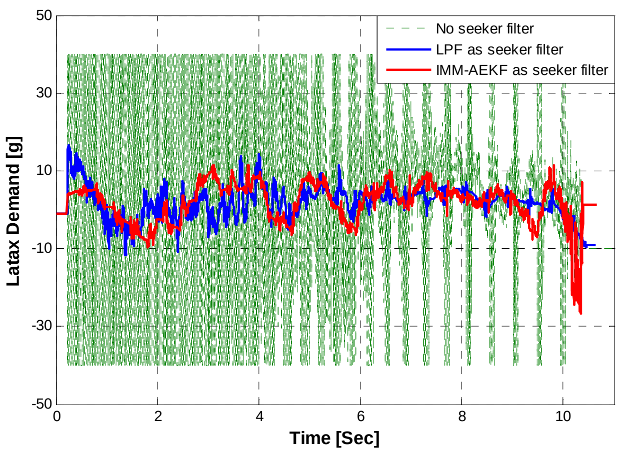

Figure 5: Latax demand generated by guidance law (Data set I)

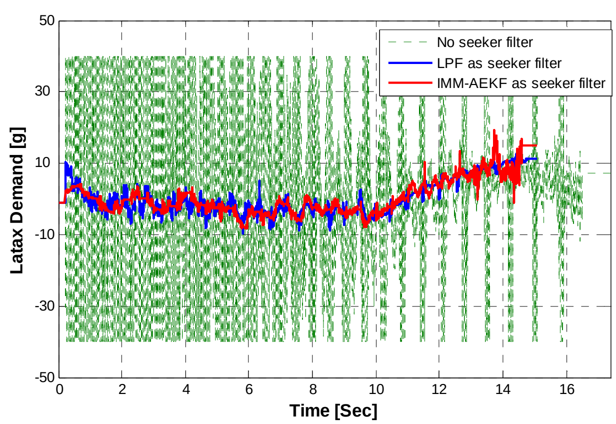

Figure 6: Latax demand generated guidance law (Data set II)

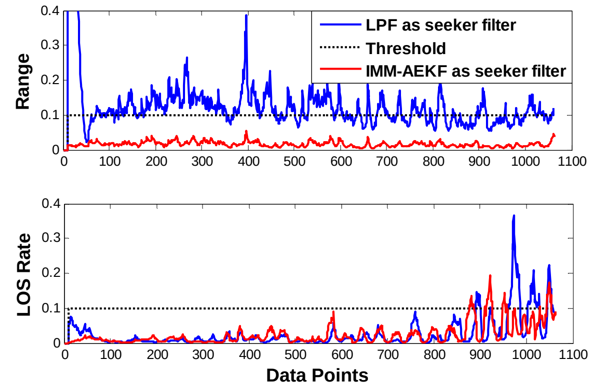

Figure 7: Noise attenuation achieved (Data set I)

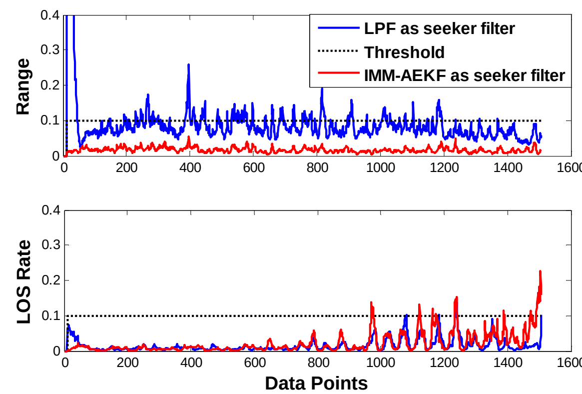

Figure 8: Noise attenuation achieved (Data set II)

IV. Concluding Remarks

This paper presents an IMM-AEKF (interacting multiple model filter with augmented extended Kalman filter as mode matched filter) seeker filters which operates in closed homing guidance loop to generate required guidance commands to intercept maneuvering air-breathing targets. The performance of the IMM-AEKF in the closed-loop is compared with that of a LPF in the closed-loop. The performance of the seeker filter is evaluated with simulation of different interceptor-target engagement scenario with different target maneuver profiles. Both LPF and IMM-AEKF seeker filters produce reasonably low latax demand. But the IMM-AEKF filter is a better choice because it not only achieve reasonable noise attenuation but also generates additional information like target acceleration often required by advanced guidance laws through a kinematic model carried by the filter.

REFERENCES

[1] Lin C F, Modern Navigation, Guidance and Control Processing, Vol. 2, Prentice Hall, 1991.

[2] Bar-Shalom Y and Chang K C, Tracking a Maneuvering Target using input estimation versus the Interacting Multiple Model Algorithm, IEEE Transactions on Aerospace and Electronics Systems, Vol. AES 26, No. 2, March, 1989

[3] Ananthasayanam M R, Sarkar A K, Bhattacharya A, Tiwari P, Vorha P, Nonlinear Observer State Estimation From Seeker Measurements and Seeker-Radar Measurements Fusion, Paper No AIAA-2005-6066-CP, 2005

[4] Wu W R, Target Tracking with Glint Noise, IEEE Transactions on Aerospace and Electronic Systems, Volume 29, No 1, pp 174-185, January ,1993.

[5] S. K. Kashyap, V.P.S. Naidu, Jatinder Singh, Girija G., and Raol J. R., “Multiple Target Tracking Using IMMPDAF”, National Workshop on Tactical Missile Guidance (NWTMG), DRDL, Hyderabad, India, Feb., 2004